7th Bangladesh Conference on Industrial Engineering and Operations Management
December 21-22, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/BA07.20240109
Published: December 21, 2024

Optimizing Coastal Defense of Bangladesh: Comparative Analysis of Stability and Cost of Different Armor Units

Shahriar Kabir Rahat, Raad Shahamat Labib and Farjana Parvin
Department of Industrial Engineering and Management
Khulna University of Engineering & Technology (KUET),
Khulna-9203, Bangladesh
kabirrahat.k20@gmail.com, labibglab17@gmail.com,
farjanamousumi17@gmail.com

Abstract

The problems due to the frequent natural calamities like coastal erosion and flooding are becoming irresistible due to Bangladesh's insufficient and inadequate embankment structures. To date, the coastal zones of Bangladesh are often overpowered by floods, erosion, and intrusion of salinity due to shedding, and poor and outdated designs of the laterite embankments. This study examines existing embankment solutions, identifying their deficiencies in design, construction, and maintenance, exacerbated by environmental and socio-economic challenges. To propose more effective coastal protection measures, this study analyzes the stability and economic viability of three different armor units: Traditional cubes, Tetrapods, and Accropodes. Stability analysis is done according to hydraulic stability coefficients, which shows the interlocking capability, as well as the effectiveness of Tetrapods and Accropodes in comparison with the Traditional cubes. Furthermore, the economic consequences describe in detail about the expenditure incurred at every stage of the armor units, which involves material, construction, and maintenance cost factors. This study also includes the design enhancement of a better armor unit among those to make that eco-friendly. The study strongly suggests that, the introduction of these technologies will not only increase the border defenses of Bangladesh's coastal infrastructure but also help reduce the effect of erosion and flooding at the coast.

Keywords
Tetrapods, Accropodes, Stability Analysis, Cost Analysis, Design enhancement.

1. Introduction
Bangladesh having a tidal shoreline of about 5,810 km is one of the worst-affected developing countries most susceptible to climate change-induced natural calamities such as sea-level rise, cyclones, and storm surges. The many millions of people who live in the coastal zone are confronted with frequent flooding and shoreline erosion that produces extensive socio-economic and environmental impacts. The embankment systems we developed to safeguard such areas are normally inadequate, compelling breaches and failures from time to time. Bangladesh has had an elaborate tradition of systems of coastal defense through the construction of embankments or more specifically formation of earthen embankments/polders, which according to Bangladesh's Coastal Embankment Project (CEP) that was laid in the 1960s currently features more than a thousand kilometers of inter-connecting structures supposed to preserve agricultural lands and human settlements from the impact of tidal waves and salinity. Spanning approximately 6,000 km and covering more than 1.2 million hectares of coastal territory, this embankment system are physical defense against floods; to provide more land that can be cultivated and increase agriculture potential. Consequently, this aspect requires a particular need for the coastal defense mechanisms to be reliable and at a reasonable cost (Uddin et al. 2022).

The traditional embankment system in Bangladesh often faces several challenges. The vast majority of such structures were built several decades ago, utilizing design standards and construction materials that have become obsolete in light of today's climate- and hydrology-related stresses. Research shows that these embankments could be failed due to the geotechnically unstable materials and indiscriminate construction practices input in place

(*Climate Change and Coastal Zone of Bangladesh: Vulnerability, Resilience and Adaptability*, n.d.). For instance, most of the embankments are built with poorly graded and highly permeable soil which make it very vulnerable to submergence and failure (Hossain 2011). Also, the embankments are even more vulnerable due to high sediment loads and shifting river channels of Bangladesh's river systems (*Helping Bangladesh Protect Its Coastal Communities from Tidal Flooding and Storm Surges*, n.d.-a).

Figure 1. Current embankment system in Bangladesh *(*Tk 50cr Embankment to Be Built in Pirojpur | The Asian Age Online, Bangladesh*, n.d.)*

Further, the existing coastal defense structures are also periodically vulnerable to climate change interventions that enhances cyclone frequencies and storm surges. The World Bank (2022) explains that frequent and intensive extreme climate events are damaging the coastal infrastructure expensively (*Bangladesh Disaster Risk and Climate Resilience Program*, n.d.). The current embankments are not designed to resist these extreme conditions, which results in frequent failures that require extensive repairs. Some of such conditions can be averted by deploying better anchored armor units like Tetrapods (Pujianiki et al. 2024), and Accropodes (Bagheshahi et al. 2024).

1.1 Objectives

To analyze the key problems associated with the current embankment systems in Bangladesh.
To compare the hydraulic stability and performance between Traditional cubes, Tetrapods, and Accropodes under various environmental conditions.
To conduct a comprehensive economic analysis of those three armor units.
To recommend design improvements for the selected armor unit to enhance ecological sustainability.

2. Literature Review

Coastal protection structures bear important functions and objectives in buffering the impacts of coastal erosion, storm surges and flooding resulting from rising sea levels. The findings establish that the existing form of coastal barriers does not have the essential capacity to cope with the increasing frequency of storms and other disasters, indicating that engineering and construction elements are required for improvement (De Almeida & Hofland, 2020). Several research works find merit in the hypothesis that sediment recycling, deployment of sediment reservoirs, and coastal tilting contribute to the enhanced vulnerability of the coasts to tidal bore, changes in tidal regime, and aggravation of erosion and flood hazard due to sea-level rise (Kuang et al. 2017). Many researchers support these findings by providing new practical design formulae for the stability of rubble mound revetments and breakwaters under random wave attack (Bars & Launay 2024). Research has laid the foundation for further studies on the stability of artificial units like Tetrapods and Accropodes, which are designed to offer greater resistance to wave forces (*Design of Breakwaters* 1988a).

Erosion protection through structures such as berms and bund walls are common on the coast of Bangladesh. A study found that several of these embankments have designs with major defects and lack proper maintenance therefore their ability to handle severe weather conditions is limited (Safa et al. 2024). Researches show that such activities remain a threat to the structures because cyclones and storm surges that are common in Bangladesh wash them away occasionally (Wernette et al. 2018). This weakness is further attributed to Bangladesh's social and economic development circumstances in as much as it has a poor resource endowment as well as poor institutions of governance that restrain the country from improving and managing shore protection status (Shariot-Ullah, 2024). The studies as a whole corroborate the importance of a concerted effort to redesign the existing and propose new embankment systems using sustainable engineering principles and reliable materials suited to addressing the dynamic and challenging nature of the coastal setting (Kuang et al. 2017).

Concrete cubes are some of the oldest forms of coast protection structures that are still in use to this date. Researches established that any concrete cubes beget weak and vulnerable to disintegration in the event they are exposed to what can be described as normal sea waves. This means there is always a high demand for their maintenance and replacement, which in turn may be costly and a burden logistically (Wernette et al. 2018). It presents the literature review of the analytical history and development of concrete cubes in the context of coastal engineering and their success in their early years due to the reason of availability of simplicity and deployment of concrete cubes (Kuang et al. 2017).

Accropodes and Tetrapods are fashioned to be able to lock together and to be able to dissipate wave energy better, the risk of getting displaced and damaged is thus minimized. The principles and purpose of Tetrapods are discussed with a focus on wave action where the peculiar geometrical structure of Tetrapods and how they fit together to be stable under high energy waves conditions are discussed (Wernette et al. 2018). Several technical requirements governing the design, construction and installation of Accropodes are provided in the ACCROPODE™ technical specifications of 2015 (*Accropode Tech Spec 2015 | PDF | Concrete | Specification (Technical Standard)*, n.d.). Studies show that using Accropodes can cut the volume of armor material demand and at the same time provide high levels of protection at a lower cost. So there is a need to apply superior engineering techniques towards combating newly enhanced dangers from climate change and rising sea levels (Kuang et al. 2017).

Hydraulic stability is a critical factor determining the effectiveness of coastal defense structures. An in-depth analysis of the hydraulic stability of various coastal defense units, emphasizing the importance of stability coefficients in predicting the performance of these structures under different environmental conditions (De Almeida & Hofland, 2020). The study shows that units such as Tetrapods and Accropodes offer superior stability compared to traditional concrete cubes, particularly in high-energy wave environments. Thus, further researches should focus on making a stability analysis in conjunction with the design process in order to be able to construct coastal protection that is capable of being robust enough to exhibit adequate performance against the nature of wave energy the particular coast will be subjected to (Kuang et al. 2017). Agreeing with these observations, studies are conducted to compare the stable nature of armor units such as Cubes, Tetrapods, and Accropodes. Research indicates that Accropodes, with their high interlocking capacity and resistance to wave forces, exhibit the highest stability among the units tested (*Design of Breakwaters*, 1988b). This is supported by the ACCROPODE™ technical specifications that defines the engineering parameters which makes those perform beyond those of other commonly known structures (*Accropode Tech Spec 2015 | PDF | Concrete | Specification (Technical Standard)*, n.d.).

It must be stated that economic factors are crucial when it comes to choosing the appropriate management measures relating to the coastal defense. Research does a good job of breaking down the cost-saving ratio of different kinds of coastal defense units. The assessment further shows that while the initial expenses of Tetrapods & Accropodes may be higher, annual maintenance and resultant repair costs remain much lower, making Tetrapods & Accropodes a wise investment in the long run (Wernette et al., 2018). However, there is generally a lack of understanding regarding the question of to what extent coastal protection infrastructure is economically justified, taking into account maintenance and repair costs as its fundamental characteristic (De Almeida & Hofland 2020).

3. Methodology

The flow chart given below demonstrates the working procedures:

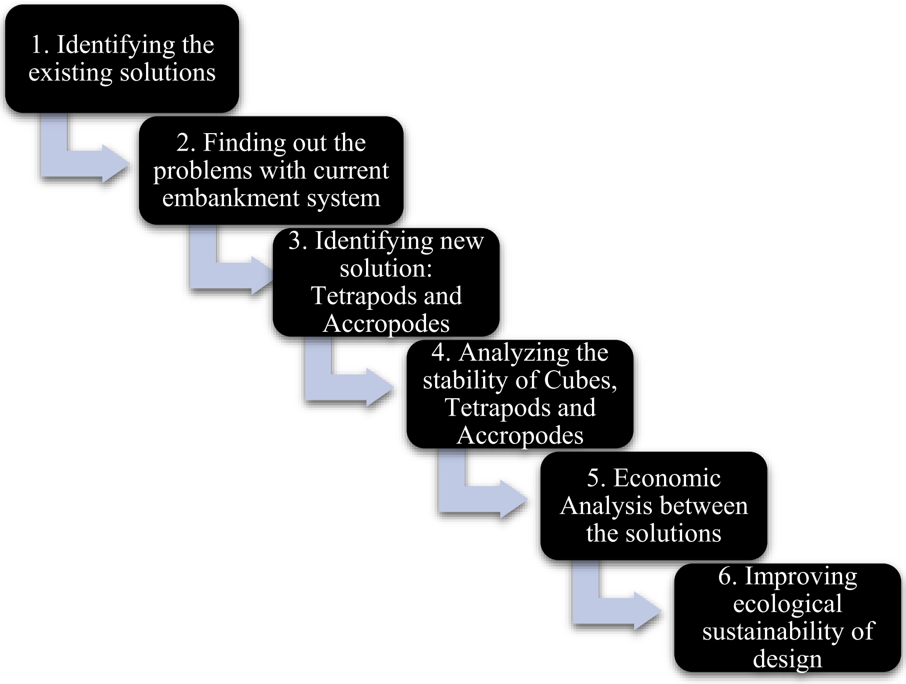

Figure 2. Flow chart of the overall procedures

Step 1. What are the existing solutions?

The existing coastal embankment system in Bangladesh consists of an extensive network of earthen embankments and polders, primarily constructed in the mid-20th century. These embankments were designed to protect the low-lying coastal areas from tidal surges, river flooding, and saline water intrusion. The existing projects are:
• Embankment Improvement Project (CEIP)
• Climate-Resilient Embankment Project (CREP)
• Sustainable Coastal and Marine Fisheries Project (SCMFP)
• Integrated Coastal Zone Management (ICZM) Project

Step 2. The problems associated with current embankment systems in Bangladesh
Concrete block revetment is widely used in Bangladesh. Concrete block revetment stability is limited to wave height of 1.5 meters. Significant wave heights are greater than 1.5 meters in the most parts of coastline.

Table 1. Typical storm surge heights for cyclones of varying strengths in Bangladesh (Huq et al., 2010)

Wave velocity (km/h)	Storm surge height (m)	Wave velocity (km/h)	Storm surge height (m)
85	1.5	195	4.8
115	2.5	225	6.0
135	3.0	235	6.5
165	3.5	260	7.8

Existing embankment solutions in Bangladesh are often not capable enough due to several interrelated factors:

1. Design and Construction Flaws**:** Most embankments were built with substandard practices and structures or materials that are not appropriate for the present hydrologic and climatic environment. For instance, materials usually applied possess low geotechnical characteristics and therefore, the structures are easily eroded especially when experienced high stress point (Hossain, 2011). The construction practices have not been very good and thus the structures have been very weak to resist even cyclone and tidal surges (*Helping Bangladesh Protect Its Coastal Communities from Tidal Flooding and Storm Surges*, n.d.-a).

2. Maintenance Issues**:** There is a serious problem of unmaintained embankments, which over time show signs of deterioration. Financial factors aggravate this problem, resulting in inadequate capital to undertake work that is required to repair or enhance assets (*Helping Bangladesh Protect Its Coastal Communities from Tidal Flooding and Storm Surges*, n.d.-b).

3. Environmental Challenges**:** The river channels are dynamic in Bangladesh and are characterized by high sediment loads that reduce the stability of the embankments. In addition, due to climate change, there are storms, and the level of the seas is also rising, and these new threats cannot be countered by the existing constructions of an embankment.(*Helping Bangladesh Protect Its Coastal Communities from Tidal Flooding and Storm Surges*, n.d.-b)

4. Socio-Economic Factors**:** Harnessing a dense population and most people living in poverty only allows for development of meager embankment systems to be established and implemented. Moreover, unintended population growth and encroachment on buildings near water bodies such as banks of rivers and along coastlines also reduce those structures' stability (*Helping Bangladesh Protect Its Coastal Communities from Tidal Flooding and Storm Surges*, n.d.-b).

5. Institutional and Governance Issues: A major relocate is that there is usually no coherent synergy between the various policy actors in the government as well as other stakeholders regarding water management and disasters. Such calamities as corruption and mismanagement can thus be seen to take resources away from strategic infrastructure development (Hossain 2011).

6. Technical and Capacity Constraints**:** Most of the embankment designs and constructions becomes suboptimal due to minimal exposure to modern engineering practices and technologies. Additionally, there is little knowledge and information about river and coastal conditions that help in design (*Bangladesh Disaster Risk and Climate Resilience Program*, n.d.).

Step 3. Identifying new solutions: Tetrapods and Accropodes
Tetrapods: Tetrapod is a type of wave dissipating concrete block planned to control, weathering and longshore drift in order to strengthen certain coastal structures like seawalls and reniforms. Tetrapods are made of concrete, and use a tetrahedral shape to dissipate the force of incoming waves by allowing water to flow around rather than against them, and to reduce displacement by interlocking ("Tetrapod (Structure)," 2024).
Several tetrapods arranged together form an interlocking, porous barrier that dissipates the power of waves and currents.

Figure 3. A tetrapod (*Tetrapod, Dolos Coastal, Erosion, Sea, Flood & Land Defence & Protection*, n.d.)

Accropodes: Accropode is a single-layer artificial armour unit developed by Sorgeah in 1981 ("Artelia" 2023). The Accropode armor unit with a rock-like appearance was developed to enhance the natural appearance of concrete armoring above low water levels. The color and type of rock-like appearance can be put with choice to blend with the environment of immediate nature ("Accropode," 2024). The framework consists of two symmetrical, bottomless half-shells that can be separated. They are also joined to form a proper mold into which the concrete is then poured. The two half-shells are separated by being struck using a jack that presses on the end of the noses (*Accropode^{TM} II Moulds | KF Moulding*, n.d.).

Figure 4. An Accropode *(*The ACCROPODE^{TM} Unit | CLI - Concrete Layer Innovations | Artelia, One of Europe's Leading Independent Engineering Firms*, n.d.)*

Step 4. Analyzing the stability of Cubes, Tetrapods and Accropodes

Stability curves for the structure are drawn below. For this, the governing variables are:

- The wave height parameter: $H_s/\Delta D_n$

- The wave steepness: ξ_z

- Slope angle: α

- The relative damage: N_0

- The number of waves (storm duration): N

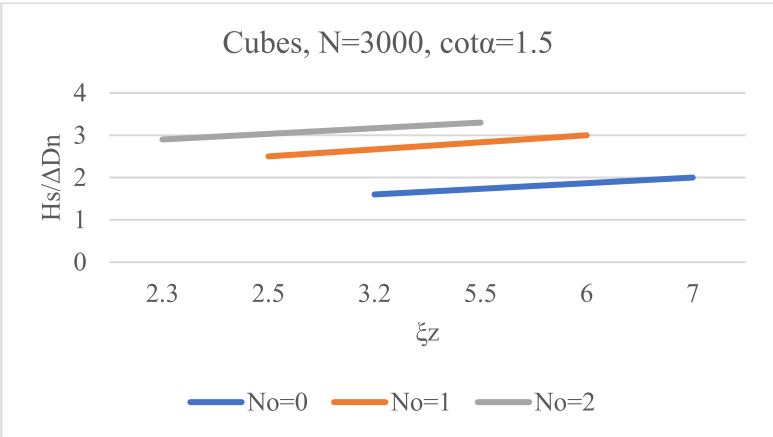

Figure 5. Stability of Cubes

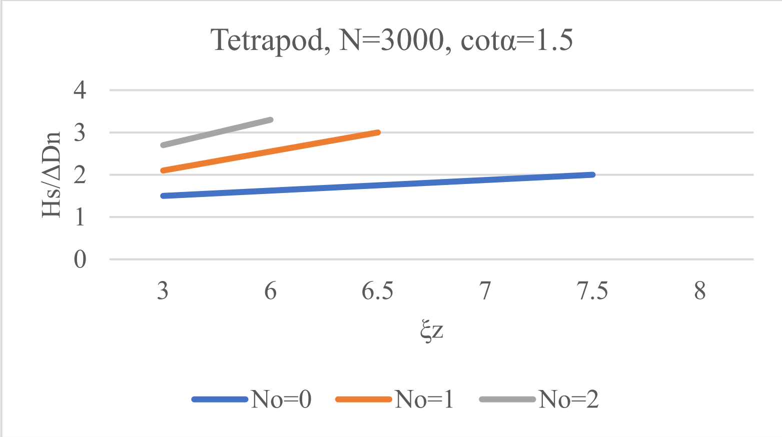

Figure 6. Stability of Tetrapods

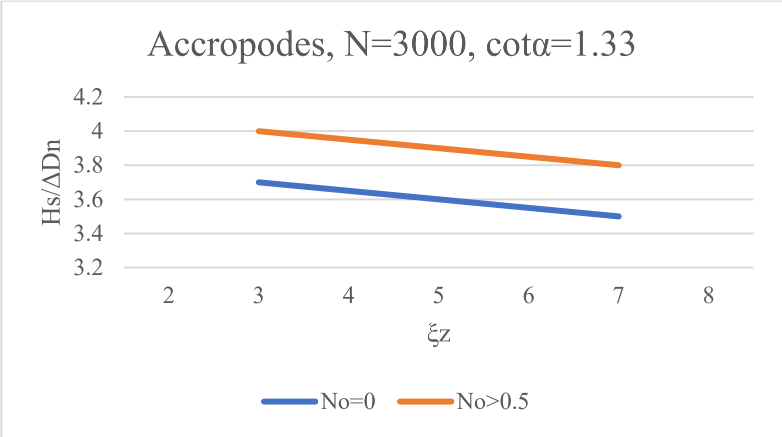

Figure 7. Stability of Accropodes

Table 2. K_D for different types of armour (Macao Airport Project, Sogreah, 2000) *(Bakker & Rovers, n.d.)*

Type of armour	Stability coefficient K_D	Slope
Tetrapod	9	1:1.5
Antifer Cube	7.5	1:1.5
Accropode	12	1:1.33

Step 5. Economic Analysis between the structures

Table 3. Costs for three types of armour (Macao Airport Project, Sogreah, 2000) *(Bakker & Rovers, n.d.)*

Type of armour	Total costs
Tetrapod	91%
Antifer Cube	100%
Accropode	57%

Table 4. Breakdown of costs (No New Coastal Embankment in 50 Years 2022)

Aspects	Costs (million in BDT per km)		
	Cubes	Tetrapods	Accropodes
Site Assessment and Feasibility	0.12	0.13	0.13
Project Design and Planning	0.04	0.06	0.06
Material	0.2	0.182	0.114
Labor	0.03	0.03	0.03
Collaboration and Partnership	0.02	0.0225	0.0225
Community Engagement	0.03	0.015	0.015
Maintenance Plan Development	0.02	0.0172	0.0104
Risk Management	0.03	0.0273	0.0171
Budget Contingency	0.03	0.04	0.1
Total	0.52	0.515	0.49

Step 6. Improving the ecological sustainability of the design

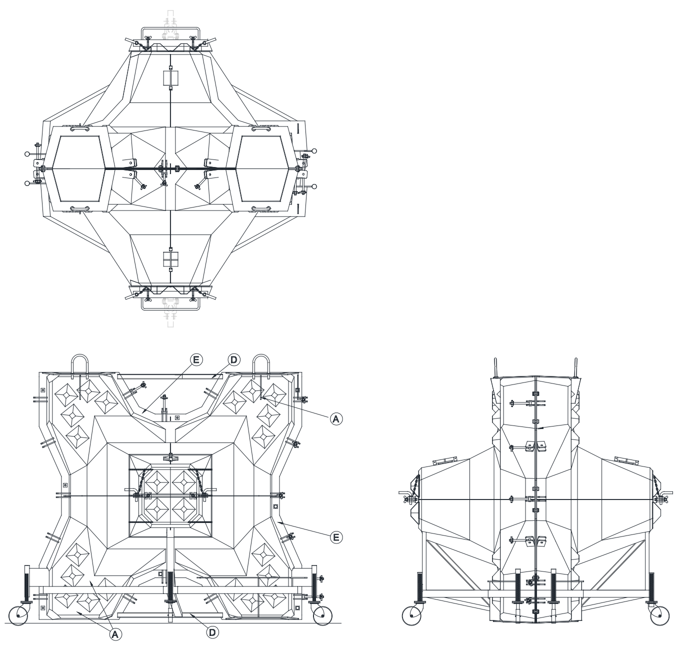

Figure 8. Design of Accropode with textured surface at AutoCAD

Introducing a rough surface into Accropodes can provide them with enhanced stability and reduced rates of erosion, fewer textured Accropodes will have to be fixed or replaced over time. This means that the use of roughness results to lower lifecycle costs as compared to the use of smooth surface. As for Textured Accropodes, they conform better to natural topography of the rocky shores, so aesthetic appearance of coastal protection structures shall be improved. And it can bring several ecological benefits such as-

Marine Habitat Creation: The rougher type of surfaces is more equipped with more locations for marine organisms to reside in, hence encouraging the variation of species. This could change the coastal defense structure into an artificial reef substrate for marine life at the coast.Improved Colonization: Semi smooth and rough surface promote the growth of algae and other species of marine angiosperms through the colonization process hence increasing the ecological importance of the structure along the coastal region. Textured surfaces on coastal defense structures, such as Accropodes, can create marine habitats through several mechanisms:

Increased Surface Area: Niches for Organisms- The irregular sculptured surfaces give multiple uneven areas that can be inhabited by various marine organisms – algae, barnacles, mussels and other invertebrates. Shelter and Protection- Those undercuts and bosses provide small marine species access to safe havens away from predators and energetic water streams.

Enhanced Attachment: Better Grip for Colonization- Such a surface increases the ability of marine organisms to secure themselves on rocks and not to be washed away by waves and streams. This is well appreciated in cases of organisms such as barnacles and mussels since they require strong adhesion to a substrate. Ecological Succession- Initial Colonization by Algae: Much as in the previous case, algal cells and biofilms comprise the primary colonizers of new surfaces. The rougher surface forms more points of contact hence the support a higher biomass from the primary immigrants. Foundation for Higher Trophic Levels- After primary colonizers get settled, they support other higher trophic level, as those feeding on algae and carnivorous ones feeding on other minor invertebrates (*The Australian Institute of Marine Science | AIMS*, n.d.).

4. Results and Discussion

The stability analysis of the coastal defense units was conducted using data and simulation models to evaluate their performance under various wave conditions. The primary units analyzed were traditional Concrete cubes, Tetrapods, and Accropodes. The stability coefficient (K_D) and the hydraulic stability number (H_s) were key parameters used in the evaluation. Concerning the economic rationale, the construction costs, maintenance costs and hence the total life cycle costs per unit were reviewed. From Table 4, it was evident that although concrete cubes incurred the least initial cost, their maintenance and replacement was constant hence incurred the highest cost in the long run. On the other hand, Tetrapods and Accropodes even though expensive to install for purchase and installation initially, they did not experience the same level of maintenance thus were cheaper in the long run. The findings therefore suggest clearly that even though normal concrete cubes are cheaper in the initial stage, their efficiency and the cost benefits are very low, compared to structures such as Tetrapods and Acropolis. It turned out that Accropodes should be considered as the most economical solution out of the three proposed ones

4.1 Numerical Results

Concrete Cubes: The analysis revealed that concrete cubes, while cost-effective, have a relatively low stability coefficient. There was evidence of quite a lot of displacement and erosion under conditions of high energy waves especially during storm surges. From Figure 5, the Hydraulic stability number of cones and concrete cubes was less than 1.5; this is potential failure in extreme condition.

Tetrapods: Tetrapods had a higher stability coefficient at the design comparison with the layer as the upper part of the structure interlocks and distributes the wave energy better. In Figure 6, we can see that the Hydraulic stability number of Tetrapods varied from 2.0 to 2.5 thereby indicating better applicability in high energy environments.

Accropodes: Among the tested units, the Accropodes were the most stable. Due to the single-layer interlocking design, Figure 7 demonstrated significantly higher resistance to wave forces with a hydraulic stability number higher than 3.0. Accropodes had the least displacement and were able to stand the most severe wave effects as simulated.
For the economic analysis, Table 5 compares the cost-effectiveness of the three armor units.

Table 5. Comparison of costs between the armor units

Cost Aspect	Concrete Cubes	Tetrapods	Accropodes
Initial Cost (per km, BDT)	0.52 million	0.515 million	0.49 million
Maintenance Cost (10 years)	High	Medium	Low
Lifecycle Cost (20 years)	Very high	Comparatively lower	Lowest between these

4.2 Graphical Results

A comparison of stability among those three armors is made in the figure below, showing for two damage levels: "Start of damage" (S_D = 2 for N_0 = 0 for artificial units) and "Failure" (S_D = 8 rock for rock, N_0 = 2 for Cubes,

N_0 = 1.5 for Tetrapods and N_0 > 0.5 for Accropodes). The curves are drawn for N = 5000 and are given as $H_s/\Delta D_n$ versus the wave steepness, ξz.

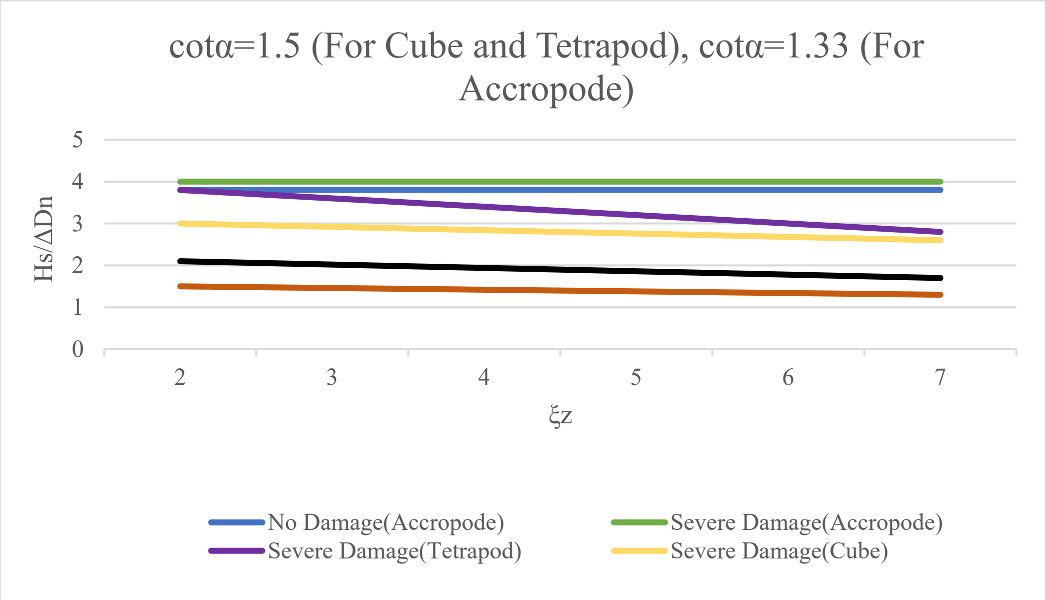

Figure 9. Comparison of Stability

The following decisions can be made:

1. Start of damage for rock and Cubes is almost the same. This is partly due to a more stringent definition of "No damage" for Cubes (N_0 = 0). The damage level S_D = 2 for rock means that a little displacement is allowed (according to Hudson's criterion of "no damage", however).

2. The initial stability of Tetrapods is higher than for Rocks and Cubes and there can be found highly improvement in the initial stability of Accropode.

3. The failure of the slope is found to be the highest in the rock and cubes compared to Tetrapods and Accropodes.

4. At the failure stage, the $H_s/\Delta D_n$ values are closer in Tetrapods and Accropodes than at the first instance of damage.

Hydraulic stability number 1.5 indicates a likelihood of displacement during wave energy events exceeding 1.5 meters, which is for concrete cubes. This displacement increases both in structural failure risks and maintenance demands. And this number is found higher in Tetrapods and Accropodes.

5. Conclusion

This research work has comprehensively compared and simulated the effectiveness and economic considerations of different coastal defense structures- conventional concrete cubes, Tetrapods– in the context of Bangladeshi coastal defense. First of all, the key problems of the current embankment systems in Bangladesh are identified. Then, the hydraulic stability and performance of Traditional cubes, Tetrapods, and Accropodes under various environmental conditions is assessed. Besides this, a comprehensive economic analysis was done to determine the cost-effectiveness of each armor unit. Those assessments conclude that among the three armors, Accropodes is the most stable and economically beneficial. Enhancing the design such as adding rough surfaces can ensure the sustainability of armor units. Apart from improving the efficiency of the measures taken for the coastal protection, this approach combined helps to achieve economic viability, an issue of import for such a country as for instance Bangladesh with its restricted fund base. Given that Accropodes are relatively new to the coast defense system in Bangladesh, the techniques used in constructing these structures are unique hence may need specialists with revelation knowledge to apply. So, identifying appropriate methods for incorporating Accropodes within the existing structure of the embankment systems is necessary. Future studies should aim at the development of the combined design that uses the benefits of current embankment systems integrated with the features of Accropodes. The results show that Accropodes represent the best option for improving coastal protection in Bangladesh. Nonetheless, issues such as complicated installation and significant initial expenses need to be tackled. Future studies should emphasize hybrid designs that integrate conventional embankments with Accropodes for enhanced performance. This can balance among cost efficiency and various environmental advantages.

6. References

Accropode. (2024). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Accropode&oldid=1195768638

Accropode Tech Spec 2015 | PDF | Concrete | Specification (Technical Standard). (n.d.). Retrieved May 31, 2024, from https://www.scribd.com/document/334844849/Accropode-Tech-Spec-2015

Accropode^{TM} II Moulds | KF Moulding. (n.d.). Retrieved May 31, 2024, from https://kfmoulding.com/accropode-ii-moulds/

Artelia. (2023). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Artelia&oldid=1174639555#Sogreah

Bagheshahi, A., Shafieefar, M., & Motalebizadeh, M. R., Experimental Evaluation of the deep toe stability of rubble mound breakwater with Accropod concrete armor. *Marine Engineering*, *20*(43), 70–79, 2024. https://doi.org/10.61186/marineeng.20.43.70

Bakker, P., & Rovers, I. (n.d.). *DEVELOPMENT OF CONCRETE BREAKWATER ARMOUR UNITS*.

Bangladesh Disaster Risk and Climate Resilience Program. (n.d.). Retrieved May 31, 2024, from https://www.worldbank.org/en/country/bangladesh/brief/bangladesh-disaster-risk-climate-change-program

Bars, S. L., & Launay, T. ,Concrete Armour Unit Breakwater Physical Model Monitoring With 3D Modeling Tools. *CoastLab 2024: Physical Modelling in Coastal Engineering and Science, 2024*. https://doi.org/10.59490/coastlab.2024.708

Climate Change and Coastal Zone of Bangladesh: Vulnerability, Resilience and Adaptability. (n.d.). Retrieved May 31, 2024, from https://www.researchgate.net/publication/234040171_Climate_Change_and_Coastal_Zone_of_BangladeshVulnerability_Resilience_and_Adaptability

De Almeida, E., & Hofland, B. , Validation of pressure-impulse theory for standing wave impact loading on vertical hydraulic structures with short overhangs. *Coastal Engineering*, *159*, 103702,2020. https://doi.org/10.1016/j.coastaleng.2020.103702

Design of Breakwaters. (1988a). Thomas Telford Publishing. https://doi.org/10.1680/dob.13513

Design of Breakwaters. (1988b). Thomas Telford Publishing. https://doi.org/10.1680/dob.13513

Helping Bangladesh Protect its Coastal Communities from Tidal Flooding and Storm Surges. (n.d.-a). Retrieved May 31, 2024, from https://www.worldbank.org/en/results/2022/08/24/helping-bangladish-protect-its-coastal-communities-from-tidal-flooding-and-storm-surges

Helping Bangladesh Protect its Coastal Communities from Tidal Flooding and Storm Surges. (n.d.-b). [Text/HTML]. World Bank. Retrieved May 31, 2024, from https://projects.worldbank.org/en/results/2022/08/24/helping-bangladish-protect-its-coastal-communities-from-tidal-flooding-and-storm-surges

Hossain. (2011). River Embankment and Bank Failure: A Study on Geotechnical Characteristics and Stability Analysis. *American Journal of Environmental Sciences*, *7*(2), 102–107. https://doi.org/10.3844/ajessp.2011.102.107

Huq, M., Khan, M. F., Pandey, K., Ahmed, M. M. Z., Khan, Z. H., Dasgupta, S., & Mukherjee, N. (2010). *Vulnerability Of Bangladesh To Cyclones In A Changing Climate: Potential Damages And Adaptation Cost*. The World Bank. https://doi.org/10.1596/1813-9450-5280

Kuang, C., Liang, H., Mao, X., Karney, B., Gu, J., Huang, H., Chen, W., & Song, H. (2017). Influence of Potential Future Sea-Level Rise on Tides in the China Sea. *Journal of Coastal Research*, *331*, 105–117. https://doi.org/10.2112/JCOASTRES-D-16-00057.1

No new coastal embankment in 50 years. (2022, May 15). The Business Standard. https://www.tbsnews.net/bangladesh/environment/no-new-coastal-embankment-50-years-419954

Pujianiki, N. N., Predana, I. M. A., Yesaya, A., Airlangga, K. G. P., Simpangan, G. R. P. A., & Ibrahim, M. S. I. B. (2024). Physical model analysis of stability coefficient for tetrapod innovation. *Journal of Infrastructure, Policy and Development*, *8*(9), 8160. https://doi.org/10.24294/jipd.v8i9.8160

Safa, E., Mojtahedi, A., Mohammadian, A., & Yaghin, M. A. L. (2024). Hydrodynamic Assessment of A New Nature-Based Armour Unit on Rubble Mound Breakwater for Coastal Protection. *China Ocean Engineering*, *38*(3), 439–452. https://doi.org/10.1007/s13344-024-0035-9

Shariot-Ullah, Md. (2024). Sea-level rise and sustainable shore protection strategies in the low-lying delta: A case study of Bangladesh. *Regional Studies in Marine Science*, *71*, 103424. https://doi.org/10.1016/j.rsma.2024.103424

Tetrapod, Dolos Coastal, Erosion, Sea, Flood & Land Defence & Protection. (n.d.). Retrieved May 31, 2024, from https://www.monaprecast.co.uk/products/monapod-tetrapod/

Tetrapod (structure). (2024). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Tetrapod_(structure)&oldid=1205455214

The ACCROPODE^{TM} unit | CLI - Concrete Layer Innovations | Artelia, one of Europe's leading independent engineering firms. (n.d.). Retrieved May 31, 2024, from https://www.concretelayer.com/en/solutions/technologies/accropode

The Australian Institute of Marine Science | AIMS. (n.d.). Retrieved June 1, 2024, from https://www.aims.gov.au/

Tk 50cr embankment to be built in Pirojpur | The Asian Age Online, Bangladesh. (n.d.). Retrieved May 31, 2024, from https://dailyasianage.com/news/61281/tk-50cr-embankment-to-be-built-in-pirojpur

Uddin, Md. J., Niloy, Md. N. R., Haque, Md. N., & Fayshal, Md. A. (2022). Assessing the shoreline dynamics on Kuakata, coastal area of Bangladesh: A GIS- and RS-based approach. *Arab Gulf Journal of Scientific Research*, *41*(3), 240–259. https://doi.org/10.1108/AGJSR-07-2022-0114

Wernette, P., Thompson, S., Eyler, R., Taylor, H., Taube, C., Medlin, A., Decuir, C., & Houser, C. (2018). Defining Dunes: Evaluating How Dune Feature Definitions Affect Dune Interpretations from Remote Sensing. *Journal of Coastal Research*, *34*(6), 1460. https://doi.org/10.2112/JCOASTRES-D-17-00082.1

Biographies

Shahriar Kabir Rahat is a passionate undergraduate student pursuing a Bachelor of Science (BSc.) degree in Industrial and Production Engineering (IPE) at Khulna University of Engineering & Technology (KUET). His research interests are in Ergonomics, Environmental Science and Supply Chain sectors.

Raad Shahamat Labib is an ambitious undergraduate student pursuing a Bachelor of Science (BSc.) degree in Industrial and Production Engineering (IPE) at Khulna University of Engineering & Technology (KUET). His research interests are in Supply Chain, Environmental Science and Operations Management sectors.

Farjana Parvin is an Assistant Professor in the Department of Industrial and Production Engineering (IPE) at Khulna University of Engineering & Technology (KUET). With a passion for teaching and research, she is dedicated to advancing knowledge in areas such as Ergonomics, Supply Chain Management, Machine Learning applications, and Materials Science.